DETERMINATION OF MINORITY CARRIER DIFFUSION LENGTH IN SOLID STATE MATERIALS

FIELD OF INVENTION

This invention relates to determining the diffusion length in solid state materials.

BACKGROUND OF THE INVENTION

The purity of the silicon wafers depends on the concentration of different impurities, including heavy metal contaminates (e.g., Fe, Cr, Cu), introduced during the manufacturing and processing of semiconductor devices. The minority carrier lifetime and the diffusion length are used for contamination monitoring in the silicon wafers. The challenge is to measure diffusion length, and monitor contamination in the product wafers at all steps of processing and manufacturing of integrated circuits.

In current techniques, the intensity-modulated light, with the photon energy larger than the band gap, is directed to the front side of semiconductor. As result of photo generation, the excess carriers change the surface potential of the semiconductor, and alternative surface photo voltage (SPV) is measured using a transparent conducting electrode placed near the front surface of the silicon wafer within the illumination area. Diffusion length is determined by measurements of the SPV signals and light fluxes under successive illuminations of the wafer with monochromatic light at different wavelengths.

The American Society for Testing and Materials (ASTM) recommends two methods, F 391 **A** and **B,** for SPV measurement of the diffusion length. The calculation of the diffusion length is based on the solution of the one-dimensional diffusion equation

for excess minority carriers assuming that diffusion length is short compared to ¼ wafer thickness.

This expression is

$$\Delta n = \Phi \frac{1-R}{D/L+S_F} \cdot \frac{\alpha L}{\alpha L+1} \qquad (1)$$

where Δn is the excess minority carrier concentration, L is the diffusion length, α is the absorption coefficient, Φ is the incident light flux, R is the reflectivity of the semiconductor, D is the minority carrier diffusion constant, and S_F is the front side surface recombination velocity. This method has been described in the patent to A. M. Goodman in U.S. Patent No 4,333,051, 1982. The SPV has monotonical dependence versus light flux with linear region for small level excitation. This method has been described in the patent to A. M. Goodman in U.S. Patent No 4,333,051 in1982.

In the first ASTM- recommended method F391 A, the magnitude of SPV is adjusted to the same value by changing the light intensity at each wavelength. The effective diffusion length is obtained from the linear plot of the light flux, Φ, versus the light penetration depth α^{-1}. The effective diffusion length equals the intercept value $L_{EFF}=-\alpha^{-1}$ at $\Phi=0$. The effective diffusion length depends on the bulk lifetime, τ, and the surface recombination velocity, *Sb*, at the back surface of the wafer. If the effective diffusion length is less then one-fourth wafer thickness, L_{EFF} can be taken to be equal to the diffusion length $L=\sqrt{D\cdot\tau}$, where τ is minority carrier lifetime.

The second ASTM recommended method F-391-**B** is the linear constant photon flux method, uses the SPV measurement for several different wavelengths of light with the same intensity, where the photovoltage has the linear dependence versus light

intensity. The diffusion length is obtained using the linear plot of inverse value of the surface photovoltage as a function of light penetration depth. This method is discussed in the patents to Lagowski, U.S. Patent No.5.025,145 and US Patent 5,177,351 and J. Lagowski et. al., *Semicond, Sci, Technol. 7, A185 (1992).* The apparatus includes halogen light source with wavelength selecting wheel for illumination and the quartz disk with indium thin oxide (ITO) film for directing the light on the wafer surface and detecting SPV signal.

In the patent to Lagowski et al., U.S. Patent No 5,663,657, another SPV probe, is used. The SPV electrode consists of the quartz disk with evaporated transparent conductance indium thin oxide (ITO) film with the diameter smaller than the diameter of the disk and hence the illumination area. The SPV probe configuration allows to diminish the systematic error of the diffusion length measurement by excluding influence of the lateral diffusion of the minority carriers in the bulk of the wafer.

In a Russian patent No 2080689 (1994), the apparatus includes a transparent and conductive electrode, the set of light emission diodes and objective lens to focus the light through said transparent electrode into a spot on the wafer. The diameter of the electrode is larger than the optical beam diameter. This configuration is different with respect to U.S. Patent No 5,663,657, where the illumination area is larger than the electrode and at the same time also eliminate error due to lateral diffusion of the minority carriers in the body of the wafer and provide better spatial resolution for the diffusion length measurement. In *Proceedings of 24th ESSDERC'94,* Edinburgh, p.601 (1994), using numerical calculations and the experiment, it was shown that this apparatus can be used

for fast mapping (2 minutes with 8000 points) of the diffusion length, with improved spatial resolution close to the optical beam diameter, d_B, even if L is comparable with d_B.

SUMMARY OF THE INVENTION

An advantage of the present invention is to provide non-contact apparatus and method for measurements of the diffusion length especially for patterned product silicon wafers.

Another advantage of the present invention is to provide a non-contact apparatus and method for diffusion length measurement in the region of scribe lines of patterned silicon wafers.

In one embodiment, the invention features an apparatus for measuring the diffusion length with high spatial resolution around 0.1-1 mm from the backside of the product wafer in its predetermined regions. This apparatus include a probe for measuring surface photovoltage from the backside of the semiconductor wafer. The probe includes an optical element, placed in proximity with semiconductor surface for directing uniform light flux onto the area of the semiconductor wafer. The probe further includes a detection element, which consists of a transparent and conducting first electrode with diameter 0.1-1 mm, coated on the surface of the said optical element close to the wafer and a conducting non transparent second electrode, connected to the first electrode and overlapping it. The apparatus also include a set of laser diodes with different wavelength installed in optical combiners, a series of optical fibers connected to the SPV probe, an optical collimator for directing light on said optical element and photo detector. The apparatus also include an optical system with CCD camera installed from the front

surface of the wafer coaxially with said optical element of SPV probe. This system is designed for pattern recognition and measurement of the diffusion length in the bulk of the wafer in the predetermined regions including the regions under testing areas located within scribe lines. Embodiments include the wafer chuck with the diameter smaller than the diameter of the wafer to get access to front and backside of the wafer.

In another embodiment of the invention the apparatus additionally includes the second SPV probe for diffusion length measurement with low spatial resolution >1 mm. This SPV probe can be used to get full wafer map of the diffusion length. The second SPV probe may include a transparent disk with a diameter>1 mm as an optical element for directing light flux onto semiconductor wafer. The transparent disk has a transparent conducting material (first electrode) covering the surface of the transparent disk. The transparent disk is placed inside of the metal ring (second electrode), which has electrical contact with the transparent and conducting material. The electrodes are connected to the preamplifier and lock-in amplifier. The apparatus also includes a set of LED's with interference filters, a series of optical fibers bundles connected to the SPV probe and directing light on said optical element – transparent disk, and photo detector.

In the third embodiment of the invention, the apparatus can include multiple SPV probes for diffusion length measurement. These multiple SPV probes can be used simultaneously at different locations on the sample, to cut the measurement time significantly, compared with a single SPV probe running in a sequential measurement mode. For example, the apparatus can include 2 SPV probes with low spatial resolution > 1 mm and 1 SPV probe with high spatial resolution 0.1 – 1 mm. One low resolution SPV probe can be used with one LED at certain wavelength, while the other low

resolution SPV probe can be used with the same or another LED at the same or different wavelength. In this way, the measurement time of multiple sites per sample can be cut in half. After measuring by multiple low resolution SPV probes, one or several specific locations (scribe lines etc.) may be measured by high resolution SPV probe.

In the fourth embodiment, the invention features a method for fast mapping of the diffusion length. This method includes one or several pulses of light at one wavelength alternating with one or several pulses of light at another wavelength. In this way, the measurement time can be cut in half.

Other advantages include but not limited to the following:

1) The SPV probe, including transparent and non-transparent electrodes, improves spatial resolution and accuracy of the diffusion length measurement by making uniform light intensity distribution inside the transparent electrode; 2) The SPV probe with reduced size of transparent electrode <1 mm provide measurements within scribe lines; 3) The apparatus and method improves accuracy of measurement of very long diffusion length; 4) The apparatus and method improves accuracy fast measurement of the diffusion length for its fast mapping; and 5) Multiple probes usage improves the apparatus throughput for wafer mapping.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic diagram of an apparatus adapted for determining a minority carrier diffusion length in predetermined areas in accordance with the invention.

Fig. 1a is an example of schematic diagram of an apparatus adapted for determining a minority carrier diffusion length in predetermined areas in accordance with

the invention in which a second low-resolution probe is installed and both low resolution probes share the same set of light sources and both low resolution probes share the same light flux detector;

Fig. 1b is an example of schematic diagram of an apparatus adapted for determining a minority carrier diffusion length in predetermined areas in accordance with the invention in which a second low-resolution probe is installed and each low resolution probe has a separate set of light sources and each low resolution probe has a separate light flux detector;

Fig. 2 is a schematic diagram of SPV probes and optical microscope arrangement in accordance with the invention.

Fig. 3 is an arrangement of the pick-up electrode for high resolution probe.

Fig. 4 is an arrangement of the pick-up electrode for low resolution probe.

Fig. 5 is a calculated plot of dependence error of the diffusion length measurement versus electrode diameter for optical beam 0.5mm for L=375 μm, 750 μm, 1500 μm.

Fig. 6 is a diagram of the light intensity and SPV signal vs time for fast diffusion length mapping if one pulse of the first light source alternates with one light pulse of the second light source;

Fig. 6A is a diagram of the light intensity and SPV signal vs time for fast diffusion length mapping if four pulses of the first light source alternate with four light pulses of the second light source;

DETAILED DESCRIPTION OF THE PREFERED EMBODIMENT

Probe and Apparatus:

Referring to FIGs. 1, 1A, 1B, 2, 3, 4, an apparatus **1** is shown for determining minority carrier diffusion length of a semiconductor wafer **2**. Briefly, the apparatus includes a grounded chuck with diameter less than the diameter of the silicon wafer **2**. The wafer chuck is mounted on the rotary stage and linear stage. For measurement in the central region the position of the wafer on the chuck is changed using robotic or other system. The apparatus also includes optical and electrical components, which give possibility to illuminate the back surface of the wafer and detect the surface photo voltage on the back surface. A first source of the light **6** consists of two or more laser LED's installed in the optical combiners. A first source of the photons **6** is coupled trough first optical fiber system **7** to first SPV transducer **8** to direct light onto back surface of the wafer. A second source of the photons **9** consists of two or more LED's with interference optical filters. A second source of the photons **9** is coupled through fiber bundle system **10** to a second back SPV transducer **11** to direct light onto back surface of the wafer. Both sources of photons are coupled to a photo detector **12**. The photo detector **12** is connected to the preamplifier and than to the computer. Probes are coupled to the look-in amplifier **13** by a computer-controlled switch **14,** so that photo voltage from both probes can be analyzed. The output of lock-in amplifier **13** is connected to the interface. Referring to Fig. 1, the apparatus includes an optical microscope with CCD camera **15** for pattern recognition, installed coaxially with the electrode of the first SPV probe **8**.

The examples of the arrangement of the apparatus including multiple SPV probes are shown at Fig. 1A, 1B. At the arrangement of the apparatus shown at Fig.1A, 2 SPV

probes with low spatial resolution > 1 mm use the same set of light sources. At the arrangement of the apparatus shown at Fig.1B, both probes with low spatial resolution > 1 mm use separate sets of light sources.

In more detail, the arrangement of the SPV probes and optical microscope is shown at Fig.2. The first SPV probe **8** includes electrode **16**, optical collimator **18** at the end of the optical fiber **7** and preamplifier **19** connected to the electrode **16**. The second SPV probe **11** includes electrode **17**, optical fiber bundle **10** and preamplifier **20** connected to the electrode **17**. Referring to Fig.3, 4 for accurate measurement of the diffusion length, the special electrodes configurations are used. The electrode **16** consists of glass or quartz disk **26** with ITO coating **21** installed inside metal **ring 25** with diaphragm **24** and dielectric ring **23**. The electrode **17** consists of glass or quartz disk **27** with ITO coating **30** installed inside metal ring **28** and dielectric ring **29**. The dimensions of these electrodes should be chosen according to theoretical calculations. Referring to Fig 5, the curves **35**, **36**, **37** are the calculated curves of a ratio of measured diffusion length to true L value for light beam diameter 0.5mm versus diameter of electrode for Ltrue =375 μm; 750 μm; 1000 μm.

For measurement of the diffusion length up to 1 mm with spatial resolution 0.1-1 mm, the diameter of the transparent disk 16 should be 0.1-1 mm and the outer diameter of the metal ring should be larger than 8 mm. This electrode configuration gives optimal signal noise ratio and lateral resolution for measurement within scribe line. This configuration is implemented in electrode **16**.

For measurement of the diffusion length up to 1 mm with spatial resolution 5 mm, the diameter of the transparent disk **16** should be 5 mm and the outer diameter of the

metal ring should be larger than 8 mm. This electrode configuration gives optimal signal noise ratio and lateral resolution for full wafer mapping of the diffusion length measurement within the scribe line. This configuration is implemented in electrode **17**.

For fast diffusion length mapping with both high and low spatial resolution, the wafer surface can be illuminated by 1 or several pulses of light at one wavelength (Fig.6, 6A), alternating with one or several pulses of light at different wavelength. An example when the wafer surface is illuminated by 4 pulses of light at one wavelength alternating with 4 pulses of light at different wavelength is shown at Fig 6A.

Diffusion length determination.

The procedure of measurement includes the following steps:

a) positioning the wafer **2** using pattern recognition system **8** to get the predetermined region of the wafer front surface over the illumination area on back side wafer surface;

b) illuminating of the back surface of the wafer **2** with monochromatic light at series of wavelength λ_i and modulating frequency f using light source **6**, optical fiber **17** and SPV probe **8** and measurement of SPV signal, V_i, using SPV probe **8** and look-in amplifier **13** and measurement of light flux Φ_l using photodiode ;

c) illuminating said area at different intensities at the same wavelength λ_1, measuring light fluxes Φ_1 and Φ_{11} and corresponding surface photovoltages V_1;

d) recalculating SPV signals using the formulas:

$$C_{NL} = \frac{V_{11} \cdot \Phi_1^2 - V_1 \cdot \Phi_{11} \cdot \Phi_1}{V_{11} \cdot \Phi_1^2 - V_1 \cdot \Phi_{11}^2}$$

$$V_i^L = \frac{1 - C_{NL}}{1 - C_{NL} \cdot V_i / V_1} V_i$$

e) determining diffusion length using values Vi^l, Φ_i and intercept of the plot Φ_i / Vi^l versus light penetration depths.

The light wavelengths can be in the range 800-1000 nm and light modulating frequency is in the range 400-5000Hz

To get full wafer map of the diffusion length, the second SPV probe can be used.

The procedure of measurement includes the following steps:

a) illuminating of the back surface of the wafer **2** with monochromatic light at series of wavelength λ_i and modulating frequency *f* using light source **9**, optical fiber **10** and SPV probe **11** and measurement of SPV signal, V_i, using SPV probe **11** and look-in amplifier **13** and measurement of light flux Φ_I using photodiode **12**;

b) illuminating said area at different intensities at the same wavelength λ_1, measuring light fluxes Φ_1 and Φ_{11} and corresponding surface photovoltages V_1;

e) recalculating SPV signals using the formulas:

$$C_{NL} = \frac{V_{11} \cdot \Phi_1^2 - V_1 \cdot \Phi_{11} \cdot \Phi_1}{V_{11} \cdot \Phi_1^2 - V_1 \cdot \Phi_{11}^2}$$

$$V_i^L = \frac{1 - C_{NL}}{1 - C_{NL} \cdot V_i / V_1} V_i$$

e) determining diffusion length using values Vi^l, Φ_i and intercept of the plot Φ_i / Vi^l versus light penetration depths.

Using the measurement of the diffusion length within scribe lines and full wafer map of the diffusion length more detail information concerning metal contamination during technological processing can be obtained.